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We demonstrate that a microelectronic circuit, the Cooper-pair box, is a coherent, quantum two-level system whose parameters can be extracted through resonant spectroscopy. The width of the resonant features implies a worst case decoherence rate of the box which is still 150 times slower than the transition rate of two-level system, even though it is inhomogenously broadened. Much slower than this decoherence rate is the rate of spontaneous decay of the excited state, which we measure by resolving in time the decay of the box into its ground state with a single electron transistor. We find a spontaneous decay rate which is 10^5 times slower than the transition rate of the two-level system, even when the measurement is active. This long lifetime and the sensitivity of our measurement will permit a single-shot determination of the box's state.

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Measurement of the excited-state lifetime and coherence time of a microelectronic circuit

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We demonstrate that a microelectronic circuit, the Cooper-pair box, is a coherent, quantum two-level system whose parameters can be extracted through resonant spectroscopy. The width of the resonant features implies a worst case decoherence rate of the box which is still 150 times slower than the transition rate of two-level system, even though it is inhomogenously broadened. Much slower than this decoherence rate is the rate of spontaneous decay of the excited state, which we measure by resolving in time the decay of the box into its ground statė with a single electron transistor. We find a spontaneous decay rate which is 10^5 times slower than the transition rate of the two-level system, even when the measurement is active. This long lifetime and the sensitivity of our measurement will permit a single-shot determination of the box's state.

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Recently, microelectronic circuits have been coaxed into behaving as quantum two-level systems (TLS) [1–5]. Although nature abounds with quantum two-level systems, such as the spins of nuclei in a magnetic field or the electronic states of dilute atomic gases, the TLS behavior of circuits is revolutionary because it demonstrates the quantum behavior of a macroscopic degree of freedom composed of many microscopic degrees of freedom. Quantum coherence was believed to be fragile in electrical circuits both because it required the complete suppression of the dynamics of the microscopic elements in a condensed matter system, and because the quantum oscillations of an electric or magnetic degree of freedom would efficiently radiate energy into the electromagnetic environment.

In this paper, we observe that under conditions of continuous measurement a microelectronic circuit, the Cooper-pair box, has the Hamiltonian of a two-level system. The parameters that appear in the Hamiltonian can be tuned experimentally with voltage and with magnetic field. We determine the Hamiltonian by a kind of spectroscopy, where we observe a resonant change in the box state when its transition frequency matches a multiple of the frequency of an applied oscillatory excitation. From the width of these resonances we can find a worst case estimate T_2^* of the coherence time of the two-level system. By placing the box into its excited state and watching it decay into its ground state we find the excited-state lifetime T_1 of the box. Based on the excited-state lifetime and the observed noise in the readout, we conclude that is possible to perform a 'single-shot' measurement that observes the box in its excited state before it has relaxed into its ground state.

The Cooper-pair box is a microelectronic circuit composed of an isolated superconducting island, attached to a superconducting lead through a thin insulating layer across which Cooper-pairs can tunnel. An additional lead, called the gate lead, lies near the island and changes the electrostatic potential of the island with the application of a voltage V_g to the gate lead through the gate capacitance C_g [Fig. 1(a)]. The island's total capacitance C_Σ is small enough that the addition of a single Cooper-pair to the island requires a large electrostatic energy, leading to suppressed fluctuations of charge on the island. Because the island is superconducting, all of the electrons form Cooper-pairs and participate in the macroscopic quantum ground state of the island. The only degree of freedom is the number of pairs n on the island. Because of the large charging energy, we need only consider two states, a state $|0\rangle$ with no excess Cooper-pairs ($n = 0$), and a state $|1\rangle$ with one excess Cooper-pair ($n = 1$), as reckoned from electrical neutrality. The Hamiltonian of the Cooper-pair box circuit is

$$\mathbf{H} = -2E_c(1-2n_g)\boldsymbol{\sigma}_z - \frac{E_J}{2}\boldsymbol{\sigma}_x \qquad (1)$$

where $\boldsymbol{\sigma}_z$ and $\boldsymbol{\sigma}_x$ are the Pauli spin matrices and n_g is total polarization charge applied to the gate electrode, $n_g = C_gV_g/2e - n_{off}$, in units of a Cooper-pair's charge [8, 9]. The offset charge n_{off} accounts for the uncontrolled potential arising from charges nearby the box island. The charging energy, $E_C = e^2/2C_\Sigma$, is the electrostatic energy required to add one electron to the island and the Josephson energy, $E_J^{max} = h\Delta/8e^2R_J$, is the effective tunnelling matrix element for Cooper-pairs across a junction with resistance R_J in a superconductor with BCS gap Δ. The junction is in fact a composite of two parallel junctions connected to form a loop with 1 $(\mu\text{m})^2$ area (Fig. 1). The effective Josephson energy E_J of the pair of junctions is tuned by introducing magnetic flux Φ into this loop, as $E_J = E_J^{max}\cos(\pi\Phi/\Phi_0)$, where Φ_0 is the quantum of flux $(h/2e)$. Equation 1 is the Hamilto-

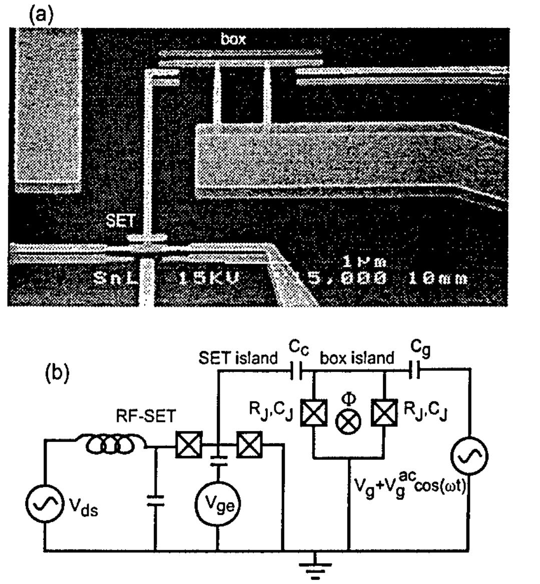

FIG. 1: (a) An SEM micrograph of the Cooper-pair box and SET electrometer. The device is made from an evaporated aluminum film (light gray regions) on an insulating SiO_2 substrate (dark gray regions) by the technique of double angle evaporation [6], which gives the double image. (b) A circuit diagram of the box and RF-SET electrometer showing: the voltage V_g and magnetic flux Φ which control the box's Hamiltonian, the quantities V_g^{ac} and ω which set the amplitude and frequency of the microwave excitation, the voltages V_{ge} and V_{ds} which determine the electrometer's operating point, and the capacitance C_C that couples charge between box and electrometer. V_{ds} includes both dc and $\approx$ 500 MHz oscillatory components [7]. The tunnel junctions (crosses in boxes) are characterized by a junction resitance R_J and capacitance C_J.

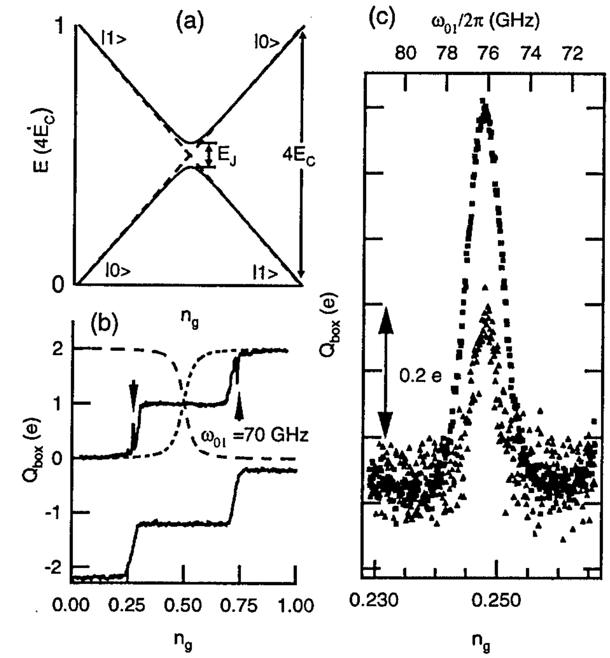

FIG. 2: (a) The ground and excited state energies versus n_g for Eq. 1, with $4E_C = 12E_J$ (solid line) and $E_J = 0$ (dashed lines). Energy eigenstates asymptotically approach charge states ($|1\rangle$ and $|0\rangle$) far from $n_g = 0.5$. (b) Q_{box} vs. n_g, calculated for the ground state (dotted line), excited state (dashed line), and measured (solid line) with 35 GHz microwaves applied to the box gate. The arrows indicate resonant peaks. Also shown is Q_{box} measured with no microwaves applied (solid line), with the y-axis shifted down by 2.2 e. (c) Two resonant peaks in Q_{box} vs. n_g on the bottom axis and vs. ω_{01} on the top axis, with $\omega = 38$ GHz and where the larger V_{ac} (squares) is twice smaller value (triangles).

nian of a quasi-spin 1/2 particle in a fictitious magnetic field that can be decomposed into two orthogonal fields. The z component of this fictitious field which accounts for the box's electrostatic energy, $E_{el}(V_g) = 2E_c(1-2n_g)$, is tuned with V_g and the x component, which accounts for the Josephson energy $E_J(\Phi) = E_J^{max}\cos(\pi\Phi/\Phi_0)$, is tuned with Φ [9].

In the box, states of definite numbers of Cooper pairs on the island are states of definite charge. In order to measure the charge of the Cooper-pair box, we fabricate the box next to a radio-frequency single-electron transistor (RF-SET)[6, 7], an exquisitely sensitive electrometer, so that the addition of a Cooper-pair to the box's island causes a small fraction (C_C/C_Σ) of the Cooper-pair's charge to appear as polarization charge on the capacitor C_C that couples the box and the RF-SET (Fig. 1). The electrometer used here had a sensitivity of 4×10^{-5} $e/\sqrt{\text{Hz}}$, 10 MHz of measurement bandwidth, and 3.7% of the charge on box was coupled into the electrometer. Because the RF-SET measures charge, its action can be described as projecting the state of the box into a state of definite Cooper-pair number. In the formal terms of Eq. 1, it measures $Q_{box} = (1+\langle\sigma_z\rangle)e$ where Q_{box} is further averaged over the measurement time. In the box, states of definite numbers of Cooper pairs on the island are states of definite charge.

We perform spectroscopy by applying a CW microwave stimulus to the gate of the Cooper-pair box, and sweeping n_g to tune the parameters of the TLS and find the resonance condition (Fig. 2. A measurement of Q_box vs. n_g shows that the box does not remain in its ground state over a range $0.3 < n_g < 0.7$. This behavior is caused by backaction [10] generated by currents flowing through RF-SET [11]. We proceed by studying the box in the range of n_g where it does remain in its ground state.

When a 35 GHz microwave signal is applied to the gate, we observe clear evidence that the box is a coherent two-level system. Resonant peaks appear [Fig. 2(b)] in Q_{box} that are sharp and symmetrically spaced about $n_g = 0.5$.

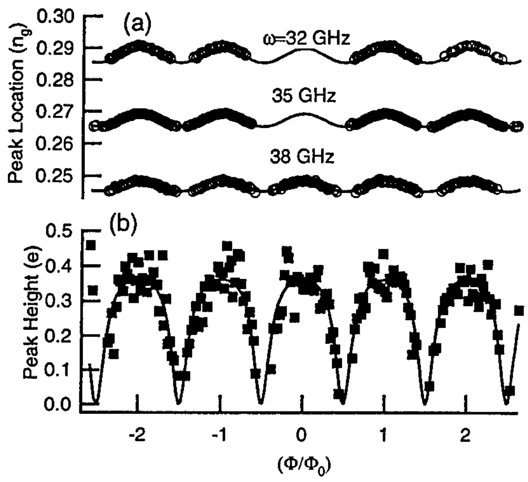

FIG. 3: (a) The locations of resonant peaks (circles) in n_g and Φ, for $\omega = 32$, 35, and 38 GHz and fits (lines), using Eq. 1 for $\omega_{01} = 2\omega = 64$, 70 and 76 GHz to find single value of E_C and of E_J^{max}. The systematic uncertainty in n_g is represented by the size of the open circle symbols. (b) The height, in electrons, of a 76 GHz resonant peak as a function of Φ (squares) and a guide to the eye (line).

The two features, a peak for $n_g < 0.5$ and a dip for $n_g > 0.5$, both correspond to the change in Q_{box} when the box spends some time in the excited state. Because Q_{box} is an average of thousands of repeated measurements, the peak height indicates the probability of finding the box in its excited state [Fig 2(c)].

The resonant peaks permit a spectroscopic determination of $E_C and E_J^{max}$. By tuning n_g and Φ while exciting the box with a fixed microwave frequency, we find good agreement between the locations of resonant peaks and the difference $E_{01}(n_g, \Phi) = \hbar\omega_{01}$ between ground-state and excited-state energy expected from Eq. 1. An independent measurement of E_C [12] demonstrates that these peaks occur when the irradiating frequency ω is half ω_{01}, indicating that these peaks correspond to a two-photon transition [13]. We find a single value for E_C and for E_J^{max} that account for the location of the resonant peaks at applied frequencies between 32 and 38 GHz giving resonant peaks for ω_{01} between 64 and 76 GHz [Fig. 3(a)]. At lower frequencies, the peaks would appear at an n_g for which the box does not stay in the ground state while being measured and are therefore not visible. Nevertheless, we are able to extract the parameters of the Hamiltonian, $4E_C/h = 149.1 \pm 0.4$ GHz and $E_J^{max}/h = 13.0 \pm 0.2$ GHz. The uncertainties arise from the systematic deviation from linearity of the function generator which created the ramp voltage for V_g. Because these measurements were made at a temperature $T < 40$ mK, they are in the limit $k_B T \ll E_J < E_C$.

Consistent with the behavior of a TLS, the peaks disappear for $\Phi = \Phi_0/2$ when E_J approaches 0, which demonstrates that E_J provides the coupling between the charge states [Fig. 3(b)] This can be understood geometrically from the fact that an oscillating gate voltage with amplitude $V_g^{ac} = 2en_g^{ac}/C_g$ adds a term to the Hamiltonian in Eq. 1 which is $n_g^{ac}\cos(\omega t)\sigma_z$, and is collinear with ground state of the quasi-spin described by Eq. 1 when $E_J = 0$. The microwave excitation therefore applies no torque which could excite the quasi-spin from its ground state [14].

The width of the resonant peaks we observe provides a worst-case estimate of the coherence time of the two-level system. As expected for a TLS, we find a broadening of the peak with increasing power of the microwave excitation. We express the width of a resonance δn_g as a width in frequency $\delta\omega_{01} = (1/\hbar)(dE_{01}/dn_g)\delta n_g$. In the absence of inhomogenous broadening, the half-width at half maximum inferred for zero power is the decoherence rate T_2 of a TLS [14]. From the width of a resonant peak that is just resolved at the lowest applied microwave power, we estimate an inhomogeneous ensemble coherence time T_2^* of about 325 ps [15]. We observe both, that the resonant peaks have a Gaussian shape, and that n_{off} drifts an amount comparable to δn_g during the two minutes required to complete a measurement, due to the well-known $1/f$ noise of single-electron devices [16]. These observations imply that the width of the peaks expresses not the intrinsic loss of phase coherence due to coupling the TLS to the environment, but rather the degree to which an ensemble of measurements are not identical. We emphasize that this coherence time is a worst-case estimate because it is extracted while the system is measured continuously by the RF-SET and because it represents an ensemble average of many single measurements that require about two minutes to complete. Nevertheless, T_2^* is about 150 times longer than $1/\delta\omega_{01}$ [Fig. 2(c)].

In order to measure the excited-state lifetime T_1, we excite the box and then measure the time required to relax back to the ground state. A 38 GHz signal is continuously applied to the gate and the box gate is tuned to $n_g = 0.248$ and $E_J = E_J^{max}$ so that the microwaves resonantly couple the ground and excited state through a two-photon transition. Abruptly, n_g is then shifted to $n_g = 0.171$ in 30 ns, slowly enough to be adiabatic but much faster than T_1. The microwave excitation no longer resonantly couples the ground and excited state, and the probability of being in the excited state decays in a time T_1. By averaging many of the transient responses to this stimulus, we find $T_1 = 1.3$ μs (Fig. 4). The lifetime is a quantity which is insensitive to slow drifts in n_{off} and demonstrates that the intrinsic quality factor [17] of the TLS, $Q_1 = T_1/\omega_{01} = 6 \times 10^5$.

We can compare this long lifetime, with the spontaneous emission rate induced by the quantum fluctuations of a generic electromagnetic environment. Calculating

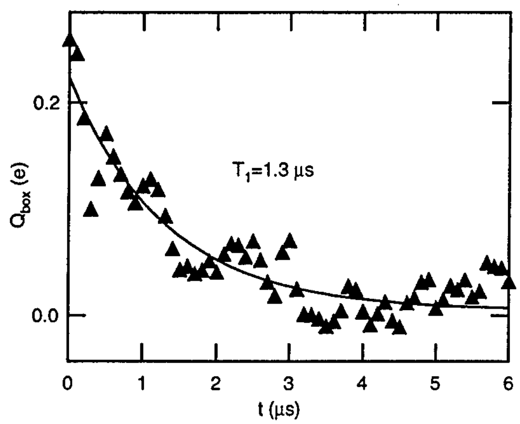

FIG. 4: Q_{box} vs. time t, (triangles), relative to $t = 0$, when n_g is shifted from $= 0.248$ to 0.171 in 30 ns, with 38 GHz microwaves applied. The shift in n_g brings the box out of resonance with the microwave excitation. An exponential fit to the data implies $T_1 = 1.3$ μs (line).

the spontaneous emission rate using Fermi's golden rule gives

$$\frac{1}{T_1} = \left(\frac{C_g^T}{C_\Sigma}\right)^2 \left(\frac{e}{\hbar}\right)^2 \sin^2(\theta) S_V(\omega_{01}) \tag{2}$$

where $S_V(\omega) = 2\hbar\omega(\mathrm{Re}(Z_0))$ is the voltage spectral density (per Hz) of the quantum fluctuations of an environment with an impedance Z_0 at frequency ω and $\sin\theta = E_J/\hbar\omega_{01}$ [9]. The quantity C_g^T is the total capacitance of the box to nearby metal traces, including intentional coupling to the gate lead and other unintended capacitive coupling (Fig. 1). We calculate T_1 for a 50 Ω environment to be between 0.25 and 1 μs, extracting C_g^T with a factor of two uncertainty from an electrostatic simulation of the chip layout [9, 11]. We do not claim to have demonstrated that the lifetime is limited by spontaneous emission; however, if there are additional relaxation processes, either due to the nearby electrometer or fluctuations of some microscopic degree of freedom in the box, their influence is at most comparable to that of spontaneous emission into a typical ($Z_0 \approx 50$ Ω) electromagnetic environment.

In these experiments, we demonstrate that a Cooper-pair box is a coherent two-level system with a long excited-state lifetime. With spectroscopy, we determine the box's Hamiltonian and estimate the rate of spontaneous emission of the box into a typical environment. We measure an excited-state lifetime of box that is remarkable for two reasons. First, it shows that a quantum-coherent microelectronic circuit can have a T_1 that approaches the limit set by spontaneous emission of a photon into the electromagnetic environment. Second, it is achieved while the two-level system is continuously measured. This means that the coherence time in the Cooper-pair box can be long lived, if the sources of inhomogeneous decoherence can be reduced [5, 17]. Furthermore, given the observed electrometer sensitivity of 4×10^{-5} e/$\sqrt{\mathrm{Hz}}$, the excited-state lifetime is long enough that a single measurement can discriminate between the box in its excited state and the box in its ground state. Both of these are vital to implementing a quantum computer.

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